

Solar Energetic Particles and Space Weather

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Abstract. The solar energetic particles (SEPs) of consequence to space weather are accelerated at shock waves driven out from the Sun by fast coronal mass ejections (CMEs). In the large events, these great shocks fill half of the heliosphere. SEP intensity profiles change appearance with longitude. Events with significant intensities of >10 MeV protons occur at an average rate of $\sim 13 \text{ yr}^{-1}$ near solar maximum and several events with high intensities of >100 MeV protons occur each decade. As particles stream out along magnetic field lines from a shock near the Sun, they generate waves that scatter subsequent particles. At high intensities, wave growth throttles the flow below the “streaming limit.” However, if the shock maintains its strength, particle intensities can rise above this limit to a peak when the shock itself passes over the observer creating a ‘delayed’ radiation hazard, even for protons with energies up to ~ 1 GeV. The streaming limit makes us blind to the intensities at the oncoming shock, however, heavier elements such as He, O, and Fe probe the shape of the wave spectrum, and variation in abundances of these elements allow us to evade the limit and probe conditions at the shock, with the aid of detailed modeling. At high energies, spectra steepen to form a spectral ‘knee’. The location of the proton spectral knee can vary from ~ 10 MeV to ~ 1 GeV, depending on shock conditions, greatly affecting the radiation hazard. Hard spectra are a serious threat to astronauts, placing challenging requirements for shielding, especially on long-duration missions to the moon or Mars.

INTRODUCTION

As we move beyond the protective shield of the Earth’s atmosphere and magnetosphere, we are exposed to sources of radiation that are a serious hazard to humans and machines. Sudden intense bursts of the solar energetic particle (SEP) events can last several days, increasing or decreasing in intensity with time (Reames 1999a, Gosling 1993, Kahler 1994). On Earth, these particles affect radio transmission and the chemistry of the upper atmosphere and ozone layer. Satellites are affected by radiation damage to electronics and to photocells that produce power and provide images. Sun sensors and star sensors used for spacecraft orientation are blinded during large SEP events. The large SEP event of 2000 July 14 saturated the SOHO/LASCO coronagraph, disabling CME observations, and saturated real-time monitors of SEPs and solar wind from the ACE spacecraft. *SEPs can blind the very systems that warn us against both SEP events and magnetic storms.*

However, the most insidious risk is to the health, and, in fact, to the very lives of astronauts from those large energetic events. As we consider long-duration missions to the moon or Mars or on the International Space Station (ISS) at high latitude, the risk from rare large events increases. Protons of ~ 30 MeV penetrate spacesuits and spacecraft walls, those of 130 MeV require 20 g cm^{-2} of shielding. Events, like that of 1972 August 4, would have been fatal to poorly shielded astronauts and large events of 1989 September and October produced significant doses, as did the event of 2000 July 14. The design of future missions that include humans: warning systems, shielding requirements, and evasion strategies, requires an understanding of the intensities and spectra of high-energy particles, and of the way that they vary in time. Fortunately, the most harmful events are rare; unfortunately, this rarity makes them impossible to study statistically. For these events we must be guided by theory and modeling based upon the fundamental physical processes of SEP acceleration and transport.

THE STREAMING LIMIT

There is an upper bound on the intensities of particles that arrive early in SEP events (Reames 1990, Ng and Reames 1994, Reames and Ng 1998). This “streaming limit” can have a major impact on 1) the probability of occurrence of events with high flux or fluence, and on 2) mission strategies for protecting astronauts from rare but lethal radiation doses (Reames 1999b).

Particles streaming along magnetic field lines generate resonant Alfvén waves that scatter other particles that follow (Stix 1962, Lee 1983). As the intensity of streaming particles increases, the wave generation also increases until there is enough scattering to sharply curtail the streaming, effectively throttling the particle flow and trapping particles near the shock. If the shock is strong enough to continue acceleration out to 1 AU, however, an intense peak can be seen later in the event when the shock itself arrives at the spacecraft. Figure 1 shows superposed proton intensity-time profiles measured for several events at low energy showing the early limit at $\sim 100\text{-}500$ ($\text{cm}^2 \text{sr s MeV}$), often followed by a delayed peak with $\sim 10\text{-}100$ times the intensity. The right panel in Figure 1 shows how the streaming limit varies with increasing energy.

Ng and Reames (1994) studied the low-energy streaming limit theoretically for a shock source near the Sun. Reames and Ng (1998) verified this limit with a large sample of events and studied the high-energy streaming limit observationally in several large events. Reames (1999b) reviewed the properties of large SEP events and suggested that the streaming limit could be used to buy time for astronauts on ISS or on deep-space missions. Intensities near Earth at the streaming limit are harmful to astronauts, but not fatal. After the onset of an event, they would have time to seek shelter before the arrival of the shock peak. In the most hazardous events, like that of 1972 August 4, the real threat comes at the time of shock passage. That event would have been lethal for minimally shielded astronauts.

It is not widely appreciated that the streaming limit also affects the size distribution of events, and existing studies of the fluence distribution in SEP events (Feynman et al. 1991) are not parameterized to consider

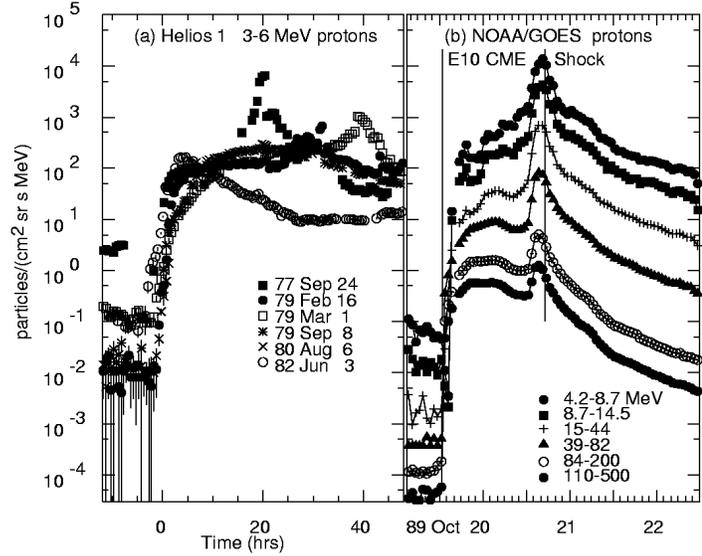


FIGURE 1. Panel (a) shows superposed intensity-time profiles of 3-6 MeV protons in several events with streaming-limited intensities early in the events. Panel (b) shows similar limits as a function of energy in the large 1989 October 19 event. Intensities often peak at the time of shock passage at values that are 10-100 times the streaming limit.

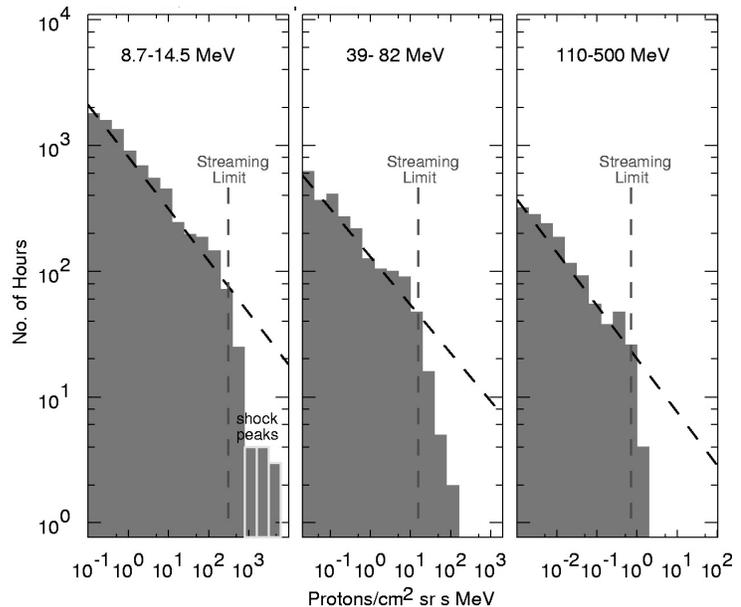


FIGURE 2. The number of hours that the NOAA/GOES spacecraft spent at a given proton intensity during an ~ 11 -year period (January 1, 1986 to September 1, 1997) are shown for three different proton energy intervals. Hours with intensities above the streaming limit come near shock peaks, as noted on the figure.

this effect. Figure 2 shows distributions of intensity at three proton energy intervals measured by NOAA/GOES. Below the streaming limit at each energy interval, the distributions are well fit as a power-law, although there may be a slight excess immediately below the streaming limit. Above the streaming limit the distributions fall rapidly, times spent at these high-intensity values occur near the times of shock peaks, as noted in the left-hand panel. The probability of a strong shock peak depends upon occurrence of a CME, near central meridian on the Sun, that is fast and powerful enough to drive a shock that remains sufficiently strong to continue accelerating high-energy particles even as it passes Earth. However, weaker CMEs from a wide band of solar longitude can drive shocks that accelerate particles near the Sun with intensities at the streaming limit. The latter are much more probable.

The distributions in Figure 2 are easily converted to distributions in peak flux, however, if we want to determine fluence probabilities for complete SEP events or for clusters of events, we must integrate over the complex time profiles of the events. These depend upon event longitude and a variety of other factors (Reames 1999a, b). The effects of the streaming limit are blurred by this process.

ELEMENT ABUNDANCES AND SEP MODELS

Once the observed proton intensities reach the streaming limit, intensities at the oncoming shock are hidden from view no matter how large they become. However, ions of other elements such as He, C, O, Si, and Fe resonate with different waves than protons of the same velocity, so these ions differentially probe the shape of the proton-generated wave spectrum between the shock and Earth. Thus, abundance ratios like Fe/O (relative to abundances in the corona or solar wind (Reames 1999a)) can be enhanced early in an SEP event because Fe escapes the shock more easily than O. Nearer the shock, Fe/O is depressed because the Fe has preferentially leaked away. Not only do abundance variations provide a means to avoid the censorship of the streaming limit, they also provide a powerful test of the new SEP models that follow the evolution of particles and waves in time and space (Ng, Reames, and Tylka 1999a, b). Figure 3 compares the complex time variation of abundances observed in the 1998 April 20 event (Tylka, Reames, and Ng 1999) with simulations based on the models (Ng, Reames, and Tylka 1999a, b). The amplitude of the abundance enhancements depends upon the ionization state, Q , of the ion and the charge-to-mass ratio, Q/A ; the resonant wave number depends linearly on Q/A for ions of the same velocity. The rise and fall of abundance enhancements in this event follows the increase and decline in wave growth as proton acceleration waxes and wanes.

One of the successes of the new theory was its explanation of differences in the initial behavior of the Fe/O and He/H abundance ratios (Reames, Ng, and Tylka 2000). If wave growth is initially weak so that all species are scattered by an ambient Kolmogorov spectrum of waves, both Fe/O and He/H should both decline with time since the species in the numerators of these ratios are scattered slightly less than those in the denominators. However, in large events with hard proton spectra, He/H rises initially. This occurs because the first protons of, say, 10 MeV, have just arrived and have yet to generate waves, however, He at 10 MeV/amu resonates with waves generated by 40 MeV protons, which arrived much earlier. This effect can be seen in Figure 4. The two events shown in the figure have similar intensities of low-energy ions, but much different behavior in He/H. However, the 1998 Sep-

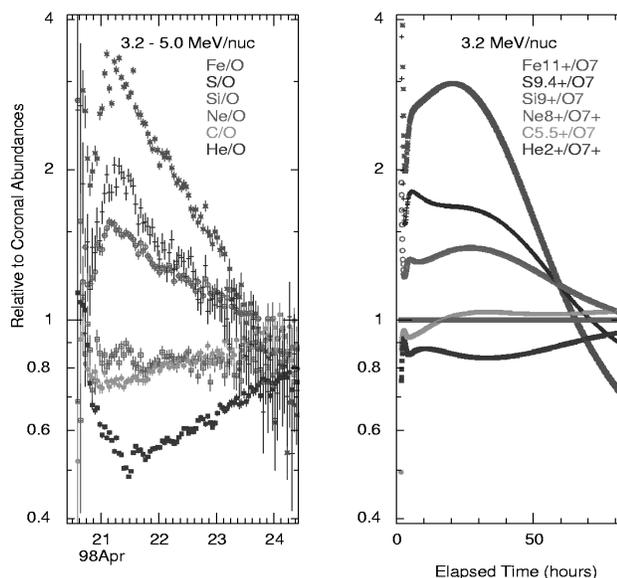


FIGURE 3. A comparison of element abundances, normalized to coronal values, in the complex 1998 April 20 event with those calculated using the theory of Ng *et al.* (1999a, b) for specific values of the ionization states shown.

tember 30 event, on the right, has much harder spectra, as can be seen in the upper panel by the 50× higher intensities of ~20 MeV protons. Relatively low-energy ions probe the spectrum of protons at much higher energies.

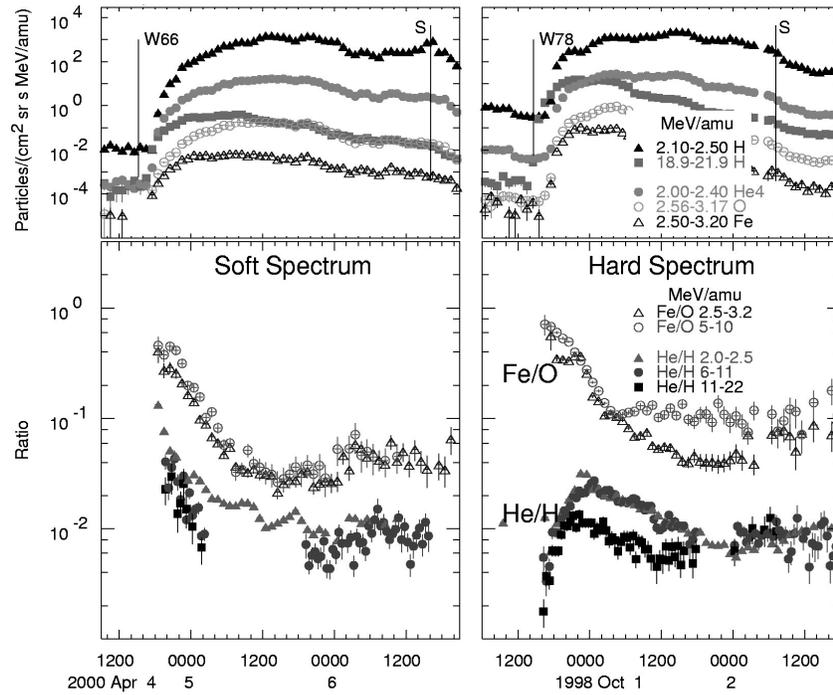


FIGURE 4. Intensities and abundances of ion species are compared for the events with soft (2000 April 4) and hard (1998 September 30) proton spectra. The initial rise in He/H results from wave-generation by high-energy protons.

SPECTRAL KNEES

As a particle scatters back and forth across a shock, it gains an increment of energy on each transit. Proton-generated resonant waves increase the scattering, improve the containment, and greatly increase the acceleration efficiency. Eventually, however, particles reach an energy where the intensities of both particles and resonant waves diminishes. There the particles begin to leak away from the shock and the accelerated spectrum steepens. This is the spectral “knee.” Ellison and Ramaty (1985) described shock spectra as a power law times an exponential; the e-folding energy of this exponential is the knee energy, E_{knee} .

Lovell, Duldig and Humble (1998) combined the energy spectrum deduced from the ground-level neutron monitor network (NMN) with that seen on

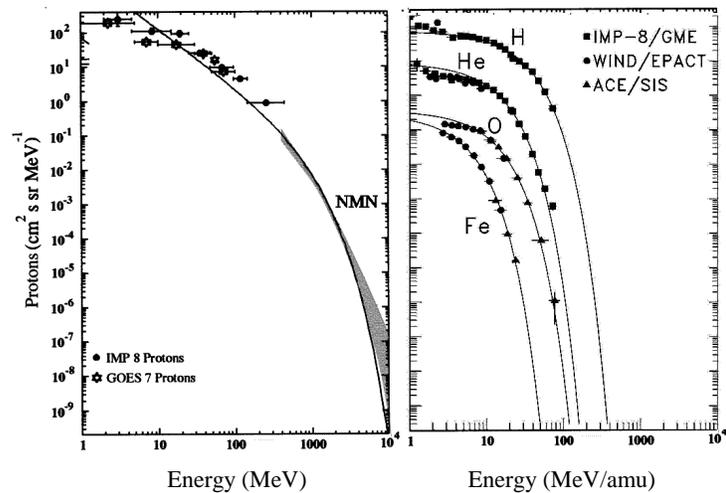


FIGURE 5. The left panel shows a spectrum from spacecraft and the neutron monitor network (NMN) in the 1989 September 29 event with $E_{knee} = 1$ GeV. The right panel shows spectra from the 1998 April 20 event with $E_{knee} = 15$ MeV for protons.

spacecraft in the large 1989 September 29 event as shown in the left panel of Figure 5. The curve shown in the figure is an Ellison and Ramaty (1985) spectrum with $E_{knee} \approx 1$ GeV. The right-hand panel in Figure 5 shows spectra for several particle species, with different knee energies, in the 1998 April 20 event (Tylka et al. 2000). In this case $E_{knee} \approx 15$ MeV for protons. This dramatic difference in E_{knee} occurs for two events that are both near the west solar limb with similar CME speeds of ~ 1800 km s⁻¹ and ~ 1600 km s⁻¹, respectively. Below about 100 MeV the proton intensities are similar in the two events.

The impact of the knee energy on radiation hazard can be seen in Figure 6 where we compare the proton spectra from the two events of Figure 5. Differences in the knee energies cause vastly different behavior above ~ 100 MeV. Soft radiation, with $E \sim 40$ MeV, begins to penetrate spacecraft walls, while hard radiation, with $E > 130$ MeV, can penetrate 5 cm of Al and becomes extremely difficult to shield. Behind 10 g cm⁻² of material astronauts would receive a dose ~ 4 rem hr⁻¹ at intensities in the 1989 September event, accumulating their annual dose limit, currently 50 rem, in relatively few hours. Differences in the knee energy alone can turn a benign event into a significant radiation hazard.

A truly serious situation would result if a high-energy knee persisted until the large peak at the time of shock passage. At this peak, streaming limits would not apply as they do in the 1989 September event, which has no shock peak. The event of 1972 August 4 is an example of high intensities of high-energy protons occurring at a shock peak; unfortunately, instrument saturation prevented definitive spectral measurements in that event. It is generally accepted that radiation levels in the 1972 August 4 event would have been fatal to inadequately shielded astronauts. The issue is the thickness of shielding required for protection. The thickness required to stop protons of given energy goes as the 1.6 power of the energy. Increasing E_{knee} from 50 to 500 MeV would increase the thickness and weight of the required shielding by a factor of 40. Mission costs increase at least linearly with payload weight, and manned missions to Mars, for example, are already expensive. Our present knowledge does not allow us to define a meaningful value of E_{knee} that is appropriate for shielding design.

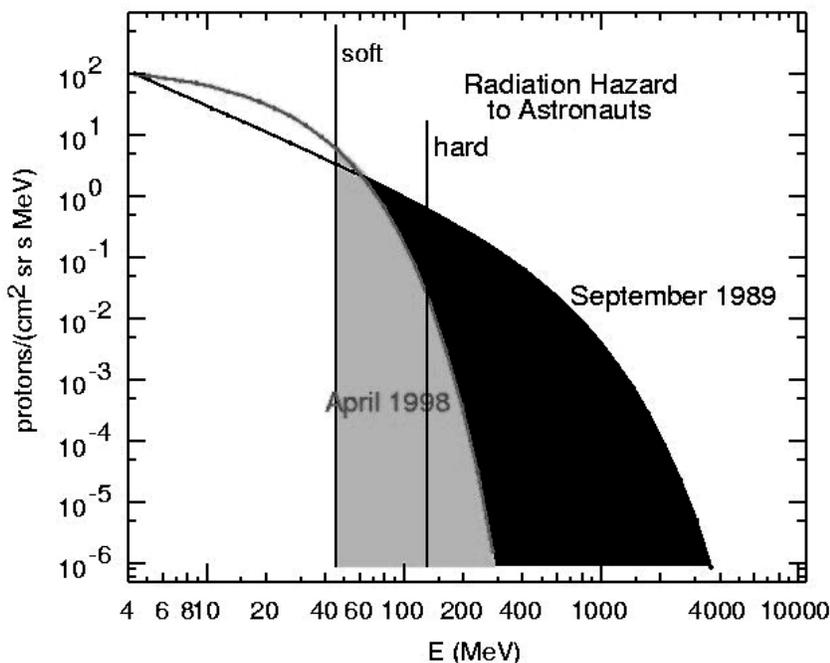


FIGURE 6. Fitted proton spectra from the two events in Figure 5 present drastically different radiation hazards to astronauts. The events are similar below ~ 100 MeV, but have greatly different knee energies.

The theory of Ellison and Ramaty (1985) relates the knee energy phenomenologically to the energy dependence of the local scattering coefficient. However, at present, there is no theory that relates E_{knee} to parameters of the shock that could be used for predictions; nor is there an understanding of the complex variation in the Q/A dependence of E_{knee} for different particle species in different events. Worse yet, measurements of proton and ion spectra above ~ 200 MeV/amu are extremely meager since most high-energy instruments are not designed to tolerate high intensities. New instruments have been proposed to address this problem, but *no instruments exist and none have been selected for flight that can measure high-energy ions in SEP events.*

CONCLUSIONS

Recent studies have revealed two important physical processes in SEP events that limit the radiation and profoundly affect the course of the event. 1) *Streaming limits bound particle intensities* in events; they greatly reduce the probability of extremely high intensities and they control the time at which they occur. 2) *Spectral knees place a high-energy limit* on events; only rarely do spectral knees reach ~ 1 GeV. The greatest radiation hazards occur when both limits are exceeded, *i.e.* in extremely fast shocks when high-energy knees persist until the time of shock passage when intensities are unbounded. Fortunately for space travel, such events are rare.

We have recently developed new models of SEP events that follow the evolution of both particles and self-generated waves in space and time. With the aid of these models and observations of element abundances, it may be possible to overcome the censorship of the streaming limit and forecast the most hazardous intensity maxima 12-24 hours before they arrive.

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